Acceleration Effects on Fluid-Sediment Interaction

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LONG-TERM GOALS

The long-term goals of this research are: (i) to identify all relevant physical processes that participate in and contribute significantly to sediment transport in nearshore coastal waters; (ii) to investigate each of the identified processes in order to understand the underlying physics in a quantitative manner; (iii) to develop simple predictive models for each process; and (iv) to incorporate the simple predictive process-models in a predictive model for beach profile response to the action of waves and currents.

OBJECTIVES

The objective of the present research is to evaluate the effect of fluid accelerations in nearshore waters. The first part of the research intended to determine the importance of the subsurface sediment transport rate induced by the pressure gradient (acceleration) associated with the passage of the front of a forward-leaning, near-breaking wave. We have concluded that this subsurface transport rate is of small importance compared with the surficial transport rate caused by shear stresses acting on the sediment bed. Consequently, the objective of the second part of the research, currently in progress, is to develop and verify the accuracy of an easily applicable methodology to compute surficial transport under near-breaking and breaking waves (hereafter referred to as *nearshore waves*).

APPROACH

We have adopted a theoretical approach to improve the existing subsurface transport model and to formulate a new methodology to compute surficial (bedload) sediment transport. The methodology is validated by comparing the model predictions with the results of a numerical model and with existing experimental data.

The *theoretical model for the subsurface sediment transport* described in our FY06 report was based on the concept of a soil-mechanics-type of failure caused by the seepage forces due to the subsurface porewater flow associated with the wave-induced pressure gradient. The procedure consisted of determining a limiting slip-circle on which the driving moment due to the wave pressure distribution on the fluid-sediment interface just balances the stabilizing moment of inter-granular shear stresses. Then, the angular rotation at any depth above the limiting slip circle was determined by applying the moment of momentum equation to the slip circle of corresponding depth. This former simplified formulation has now been improved (i) to account for the relative displacement between concentric annuli within each circle, and (ii) to evaluate the effect of interstitial pressure attenuation with depth.

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A *simple theoretical model for the surficial sediment transport* along the sediment-water interface (bedload transport) due to shear stresses associated with nearshore waves has been developed. Based on our understanding of the physical mechanisms that govern the boundary layer development under asymmetric and skewed breaking waves, it is concluded that the bed shear stress can be parameterized in terms of the near-bed velocity through a generalized, time-dependent friction factor. For cases in which bedload is the dominant transport mechanism, the total sediment transport is proportional to the 3/2 power of the bed shear stress. Thus, we have developed a computationally efficient methodology to predict bedload transport, suitable for application in coastal engineering practice.

A numerical model of the wave boundary layer has been used to validate our simple model's theoretical predictions of the bed shear stress. The numerical model is based on a standard k-ε turbulence closure. In addition, existing experimental data have been used to evaluate the accuracy of the sediment transport rate predictions of our bedload transport model.

Personnel carrying out the research are, in addition to the PI, the graduate student research assistants Mr. William Durham and Mr. David Gonzalez-Rodriguez. Mr. Durham received his Masters Degree in February 2007 and Mr. Gonzalez-Rodriguez will receive his PhD degree, both based on theses derived from this research.

WORK COMPLETED

In the first part of the research, the subsurface failure mechanism is now represented as a series of concentric *slip annuli* rotating about their common center *C*, instead of using *slip circles*. One of these annuli, of radius *r* and differential thickness *dr*, is shown in Figure 1. The moment of momentum principle is applied to each annulus, which yields the dynamic equation

$$\frac{dI}{dr}\frac{d^2\theta}{dt^2}+\frac{dm}{dr}gr\theta=\left[-p_b(x)+p_b(x+l_s)\right]r-\frac{dM_s}{dr}, \tag{1}$$

where $I(r)$ and $m(r)$ are the moment of inertia and the mass of the *slip circle segment* of radius *r*, and $M_s(r)$ is the stabilizing moment due to the inter-granular shear stress along the arc of radius *r*. The driving moment (the first term on the right-hand side of Eqn. 1) is evaluated in time by translating the spatial bottom pressure distribution, $p_b(x)$ (shown in Figure 1), past the location of failure assuming the wave to be of permanent form, i.e., taking $x = c\,t$. It is noted that, in contrast to our former approach, Eqn. 1 accounts for the slip between each annulus and both its immediate *lower and upper* neighbors.

Instead of assuming the pore pressure to be hydrostatic and linearly varying along the slip circle, we now compute M_s using the actual pore pressure distribution along the annulus. Under the assumption of quasi-steadiness, we derive an analytical expression for the pore pressure in the soil induced by a sinusoidally varying pressure on the bed. Then, we write the actual pressure applied on the bed as a sum of Fourier components and obtain the pore pressure associated with each component. Finally, the total pore pressure is obtained by adding the contributions from all the Fourier components.

In the second part of the research, a simple methodology for computing bed shear stresses and bedload transport under nearshore waves has been developed. The methodology is based on a conceptualization

of the physics of the boundary layer due to the near-bed velocity of nearshore waves, u_b. The typical shape of u_b is presented in Figure 2. As shown in the figure, nearshore waves are both skewed (with peaked, narrow crests and flat, wide troughs, i.e., $u_c > u_t$) and asymmetric (forward-leaning in shape, i.e., $T_c < T_t$). The skewed shape induces a larger onshore velocity and thus a larger onshore bed shear stress. The asymmetric shape has a similar effect, although the underlining physical mechanism that causes it is more subtle. At point *B*, the near-bed velocity changes sign, and a new boundary layer due to the positive near-bed velocities starts developing (see Figure 2). The maximum onshore bed shear stress is associated with this boundary layer that develops during a time $T_{cp}/4$. The boundary layer process for the negative velocities (after point *D*) is analogous. In an asymmetric wave, $T_{cp} < T_{tn}$, and the boundary layer associated with the onshore bed shear stress has a smaller time to develop and consequently a smaller thickness. Therefore, the maximum onshore bed shear stress will be larger than the maximum offshore shear stress even for an asymmetric but non-skewed wave. Since the net cross-shore transport is the small difference between the onshore transport (due to onshore bed shear stress) and the offshore transport (due to offshore bed shear stress), both wave skewness and asymmetry appear to have a crucial effect on the net bedload transport rate.

Based on the previous considerations, we propose a simple analytical model for the bed shear stress, τ_b. We generalize the classical formulation for a sinusoidal wave by introducing a time-dependent friction factor, $f_w(t)$, such that

$$\tau_b(t - t_\varphi) = \frac{1}{2}\rho f_w(t)|u_b(t)|u_b(t), \tag{2}$$

where ρ is the water density and t_φ is the time lag between the near-bed velocity and the bed shear stress. When $u_b(t) > 0$, $f_w(t)$ is taken equal to the friction factor of a sinusoidal wave of period T_{cp} and velocity amplitude u_c. When $u_b(t) < 0$, $f_w(t)$ is taken equal to the friction factor of a sinusoidal wave of period T_{tn} and velocity amplitude u_t. The bed shear stress predictions afforded by Eqn. 2 are compared with those of a numerical model with a standard *k*-*ε* turbulence closure. With the bed shear stress computed from Eqn. 2, the bedload transport is readily obtained using a Meyer-Peter and Müller-type bedload formula (Madsen, 1991), which has been extended to account for the effects of bottom slope.

RESULTS

In Figure 3 we show a sample comparison between the theoretical results of the former and the improved subsurface transport model, corresponding to experimental conditions described in our FY06 report. In the figure, the blue, dotted line represents subsurface forward displacements predicted by the former slip circle model with hydrostatic pore pressure distribution. The model yields good agreement with the measured displacement at the fluid-sediment interface ($z = 0$). The green, dashed line corresponds to the predictions by the slip annuli model with hydrostatic pressure distribution. On the interface ($z = 0$), both models yield similar results, since the uppermost slip annuli coincides with the uppermost slip circle. However, the predicted displacement by the new model for $z<0$ is smaller than that of the former model. This is due to the fact that the new model accounts for the movement of the slip annuli above the depth of interest. Consequently, in the new model, part of the driving moment of momentum is being used in moving the slip annuli above, and the remaining moment to drive the slip annulus of interest is decreased. The red, solid line represents the most refined model, which accounts

for non-hydrostatic pore pressure in the soil. As seen in the figure, this second refinement does not affect significantly the predicted displacements.

The conclusion drawn from the results obtained from the former slip circle model and the experiments was that the subsurface transport mechanism appeared to account for a small fraction of the total sediment transport in the nearshore (at most ~10% of the total). The improved theoretical model yields subsurface displacements that are even smaller than the less accurate slip circle model. Therefore, our recent work confirms our previous conclusion that the subsurface transport does not seem to play a major role in the transport of sediment within the nearshore region. For this reason, we changed the focus of our research to the study of surficial shear-stress-induced sediment transport.

As outlined in the previous section, to estimate bedload sediment transport it is necessary to accurately predict the bed shear stress due to nearshore waves. We have compared the predictions of our simple, analytical model for the bed shear stress with the results obtained from the computationally intensive, standard numerical model for a number of trial waves, representative of different degrees of asymmetry and skewness observed for nearshore waves. The results of the two models show excellent agreement (Figure 4), suggesting that our simple analytical model successfully captures the essential mechanisms that govern the wave boundary layer.

With our predictions of the bed shear stress and using a bedload transport formula (Madsen, 1991) we can predict bedload transport under nearshore waves. We have found that our bedload predictions are in excellent agreement with oscillatory water tunnel measurements for asymmetric waves and for skewed waves from the literature, provided that suspension effects (not accounted for by the model at the present stage) are negligible. To determine the importance of suspension effects, we use the parameter u_{*m} / w_s , i.e., the ratio between the maximum shear velocity and the settling velocity. From theoretical considerations, we expect that the suspension effects will become important and our bedload formula will no longer yield accurate predictions when $u_{*m} / w_s > \sim 2.5$. Comparing our predictions with measurements, we observe very good agreement for cases with $u_{*m} / w_s < \sim 2.7$, with predictions and measurements increasingly diverging beyond this threshold.

The bedload predictions of the analytical model are first compared with measurements of sediment transport rates due to sinusoidal waves propagating over a plane sloping bottom. The measurements include cases with positive, negative, and zero bottom slope. The good agreement between predictions and measurements demonstrate the ability of our bedload model to capture the effects of bottom slope.

Figure 5 shows a comparison between predicted and measured average sediment transport rates for the asymmetric wave data by King (1991). Only those cases with $u_{*m} / w_s < \sim 2.7$ are presented in the figure. The data includes cases with forward- and backward-leaning waves. King’s experiments were run for half a wave cycle and the measured transport rates correspond to onshore wave velocity only. Comparisons between the analytical and numerical model for impulsively started near-bed velocities support the applicability of the analytical model to King’s data. As shown in the figure, the predictions and measurements are in excellent agreement, especially when considering that the model has been applied *without tuning* any parameters to fit the data, i.e., the model is truly predictive. We have performed similar comparisons for oscillatory water tunnel experiments for periodic (full cycle) skewed waves, with similarly good agreement, as shown in Figure 6.

IMPACT/APPLICATIONS

From the results of the subsurface transport modeling, we conclude that the pressure-gradient-induced subsurface transport mechanism is, under usual nearshore conditions, of secondary importance, as it accounts for at most ~10% of the total transport. Therefore, for most practical engineering applications, its effect may safely be neglected. However, before completely abandoning the subsurface transport mechanism, our new model's sensitivity to limiting slip circle geometry will be ascertained.

After recognizing the unmatched importance of the surficial sediment transport, we have developed a physically-based methodology to compute bedload transport under pure waves in the nearshore region. Our methodology only requires very simple calculations, which makes it readily applicable to predict bedload transport due to realistic nearshore waves provided that (i) suspension effects are not important and (ii) an estimation of the near-bed velocity is available. The expected importance of suspension effects can be evaluated from the model's predictions. The near-bed velocity is easily predicted as a function of the local wave height, period, and depth, by using existing parametric relationships. Therefore, our simple analytical model provides a valuable tool to obtain estimates of bedload sediment transport under pure waves in engineering practice. The effect of (i) combined waves and currents and (ii) suspended sediment transport will be the objectives of future work.

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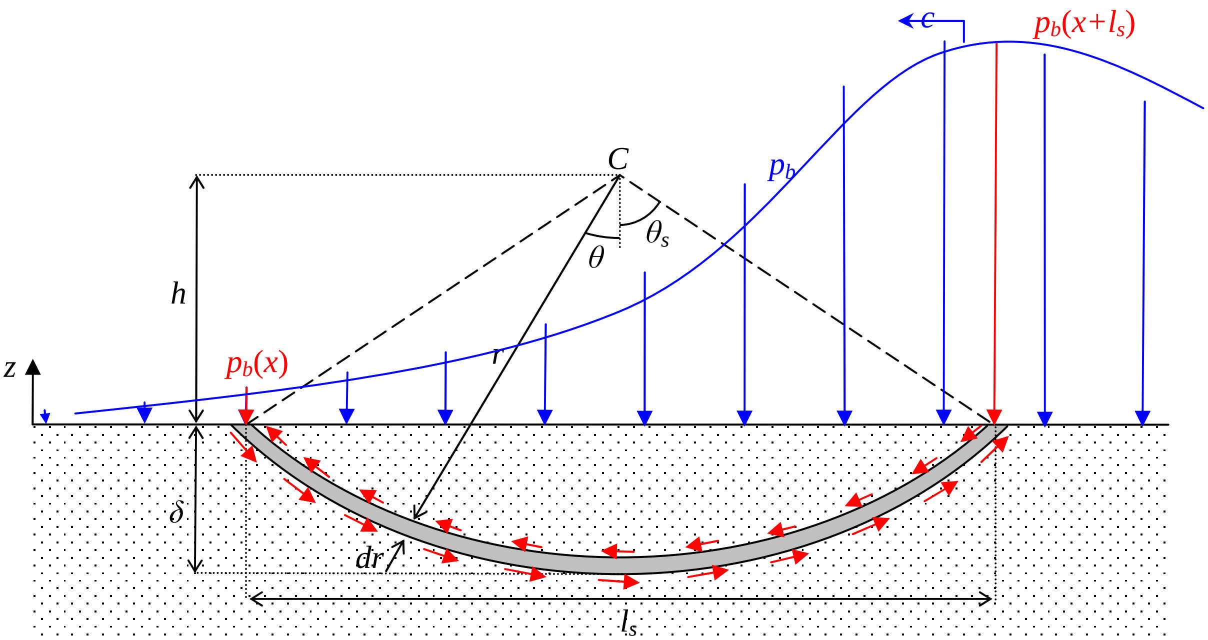

Figure 1: Geometry and force balance for a slip annulus.

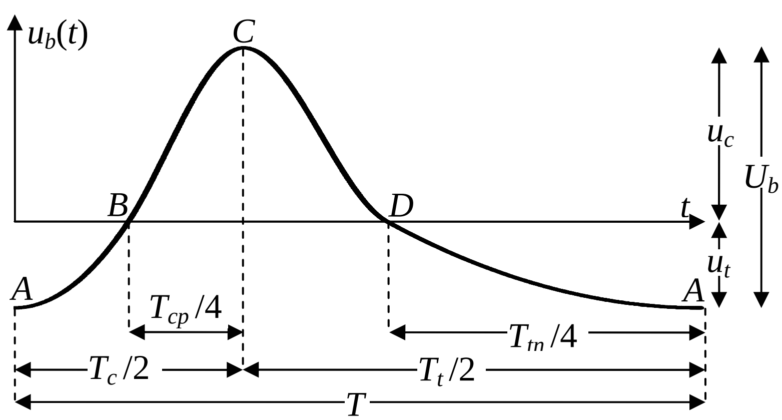

Figure 2: Asymmetric and skewed near-bed velocity induced by a nearshore wave. Adapted from Gonzalez-Rodriguez and Madsen, 2007. [The figure shows a rapid increase of velocity between the zero-upcrossing (point B) and the crest (point C), and a slow decrease of velocity between the zero-downcrossing (point D) and the trough (point A), as is characteristic of an asymmetric wave. The time interval between B and C is T_{cp}/4. The time interval between D and A is T_{tn}/4.]

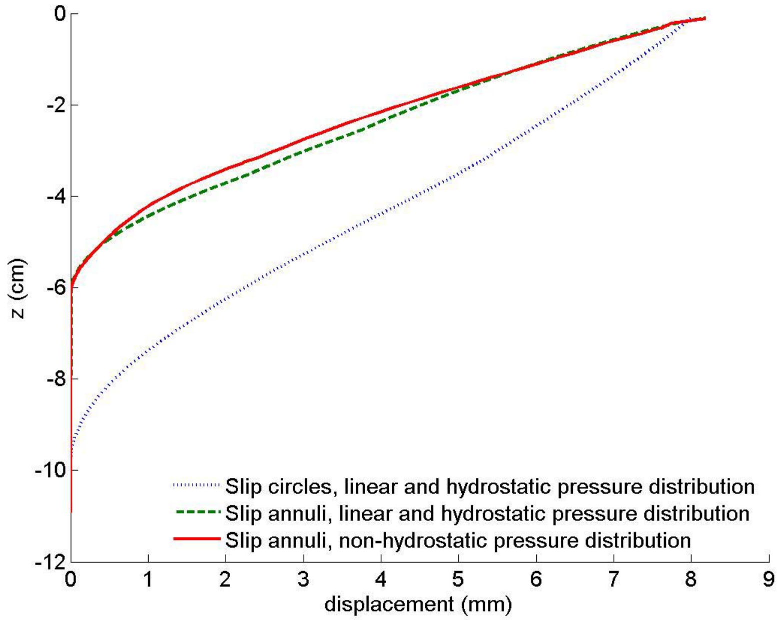

Figure 3: Effect of the introduction of the slip annuli approach and the pore pressure variation in the predicted subsurface displacements. [The figure shows a comparison between three models: (1) slip circles with linear and hydrostatic pressure distribution, (2) slip annuli with linear and hydrostatic pressure distribution, and (3) slip annuli with non-hydrostatic pressure distribution. The three models predict the same displacement at the sediment-water interface, while models (2) and (3) predict a smaller displacement within the bed.]

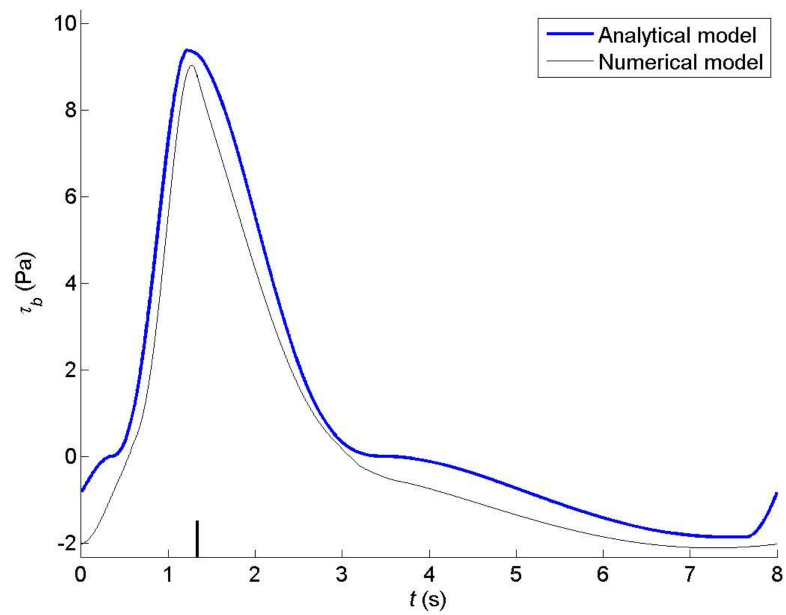

Figure 4: Comparison between bed shear stress predictions by the analytical model (blue) and the numerical model (black) for an asymmetric and skewed wave. Adapted from Gonzalez-Rodriguez and Madsen, 2007. [The bed shear stress predictions of both models agree in magnitude and phase. The maximum and minimum shear stress predictions differ by ~5%.]

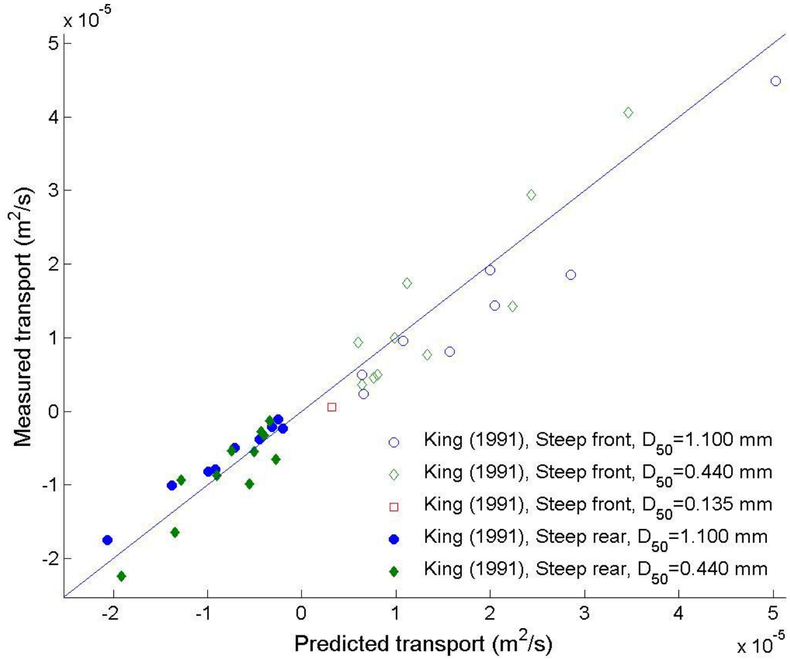

Figure 5: Comparison between measured and predicted average sediment transport rates under asymmetric and non-skewed waves. Adapted from Gonzalez-Rodriguez and Madsen, 2007. [The measurements correspond to asymmetric waves with steep front and steep rear measured by King (1991). The mean diameters range from 0.44 to 1.1 mm for different experimental cases.]

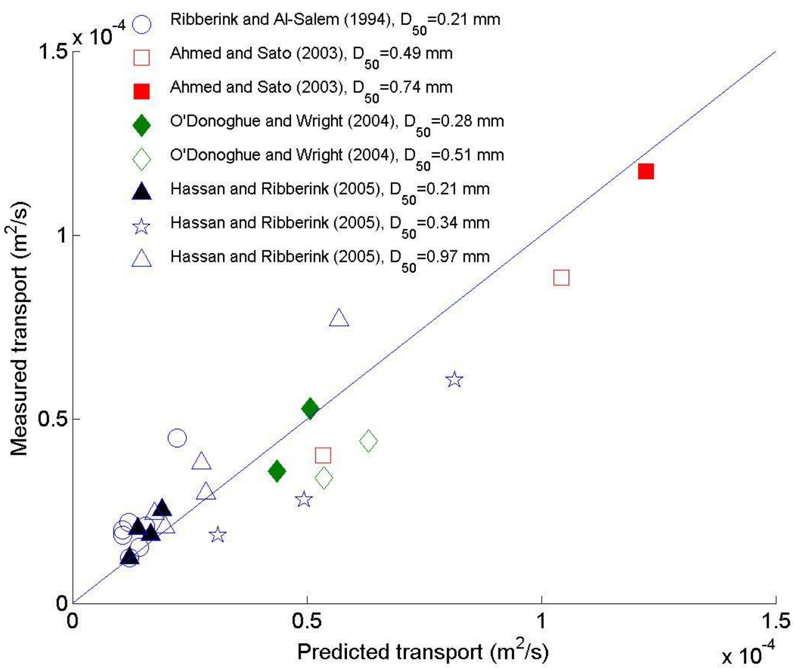

Figure 6: Comparison between measured and predicted average sediment transport rates under symmetric and skewed waves. Adapted from Gonzalez-Rodriguez and Madsen, 2007. [The measurements correspond to skewed waves measured by different authors. The mean diameters range from 0.21 to 0.97 mm for different experimental cases.]